Jupiter Radiation Test Levels and Their Expected Impact on an Encounter Mission*

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Upper limit electron and proton fluences for a Thermoelectric Outer Planet Spacecraft (TOPS) mission in a near-Jupiter environment, for use as radiation design restraints, have been extracted from the JPL engineering model of the Jovian trapped radiation belts. Considerations of radiation effects in semiconductor devices have been employed to construct simplified radiation test levels based on the design restraints. Corresponding levels, based on the nominal belt models, are found to be one to three orders of magnitude smaller. In terms of expected radiation-induced degradation in semiconductor devices, an encounter with an environment as severe as the design restraints would require hardening the system in order to guarantee high reliability. On the other hand, the nominal levels would only necessitate care in the selection of components and the avoidance of certain discrete semiconductor piece-parts.

The possible existence of prominent trapped radiation belts of energetic electrons and protons at Jupiter constitutes a serious hazard to any spacecraft in the vicinity of the planet. This radiation environment is hypothesized from the observation of apparent synchrotron emission from relativistic electrons and from analogy with Earth. A JPL engineering model (ref. 1) has been constructed based on several of the scientific models of the Jupiter trapped radiation belts, as discussed in a previous paper by Divine. In this model, the differential flux for either protons or electrons has the form:

$$\frac{d\Phi}{dE} = \frac{E v(E) N_0(L,\phi')}{E_0^2(L)} \exp\left[-\frac{E}{E_0(L)}\right]$$

where the characteristic number density N_0 is a function of the magnetic shell parameter L and the magnetic latitude ϕ', the characteristic energy E_0 is a function of L, and the speed v is a function of E.

DETERMINATION OF THE WORST CASE

In order to establish design constraint levels, the most severe environment permitted by the engineering model must be determined. Unfortunately, the functional dependences of E_0 and N_0 have large uncertainties, especially in the case of protons. The assumed dependence is constant from L = 1 to L = 2 and then decreasing according to an inverse power law. For any given trajectory, the severest dependence for N_0 is the slowest drop-off or the smallest exponent allowed by the model. Also, the largest peak (L = 2) value of N_0 is chosen. Since N_0 decreases with increasing magnetic latitude, the more severe trajectories lie in the magnetic equatorial plane. As will be shown, the selection of E_0 and its dependence for the worst case requires a consideration of the radiation damage in semiconductor devices.

RADIATION DAMAGE IN SEMICONDUCTORS

At the flux levels under consideration here, the two mechanisms for the degradation of semiconductor devices are ionization and displacement. Joule heating from induced electrical current is not a problem. Both the protons and electrons cause ionization, but the effect is long-lived only for a small class of devices, the metal-oxide-semiconductor (MOS) types, where the induced charge can be trapped. Displacement damage, or the removal of an atom from its proper lattice position, is more efficiently induced by protons than by electrons. This permanent effect, which will anneal at a temperature-dependent rate, is most harmful to minority carrier or bipolar technology devices.

For electrons, the severity of the ionization damage, which is proportional to the stopping power dE/dx shown in figure 1 (ref. 2), increases slowly with energy for energies greater than 0.7 MeV. The range curve in figure 1 (ref. 2) indicates that electrons of lower energies will not penetrate 50 mil of aluminum, a typical spacecraft wall thickness, and may be ignored. Another source of ionization from electrons, gamma bremsstrahlung production in the spacecraft wall, is negligible under these assumptions (ref. 3). The relative displacement damage as a function of electron energy (ref. 4), shown in figure 2, indicates clearly that higher energy electrons are more damaging. On the basis of both ionization and displacement damage, the worst-case characteristic energy is the highest allowed by the model.

By contrast, for protons in the energy range of interest, both the stopping power (ref. 2) in figure 3 and the relative displacement damage (ref. 4) in figure 4 decrease with increasing energy. Thus, low energy protons are the most damaging. However, the range curve (ref. 2) in figure 3 indicates that the characteristic energy

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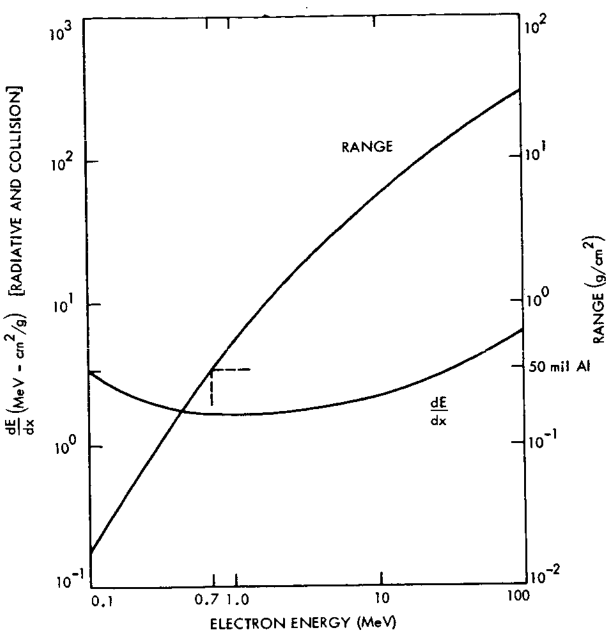

Figure 1. -Stopping power and range curves for electrons in silicon.

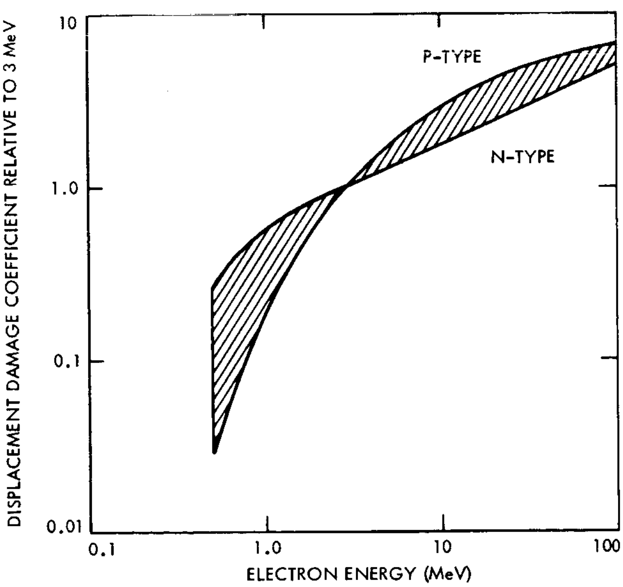

Figure 2. -Relative electron displacement damage in silicon.

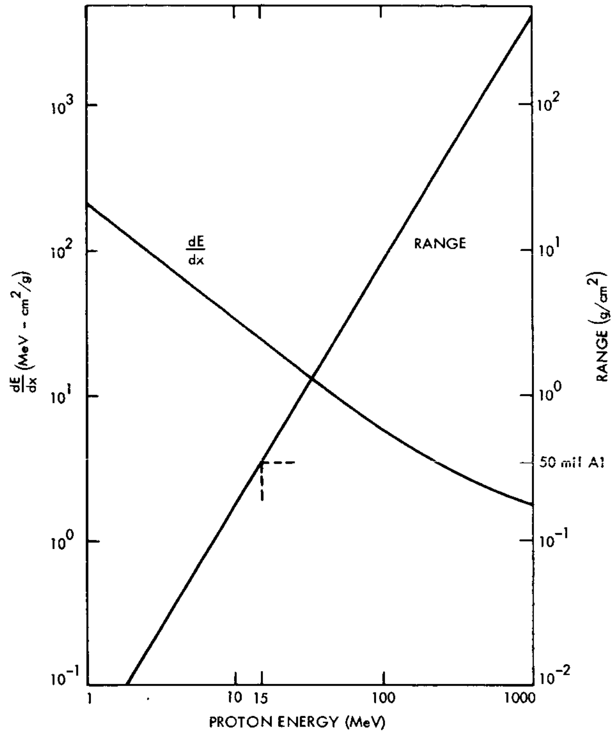

Figure 3. -Stopping power and range curves for protons in silicon.

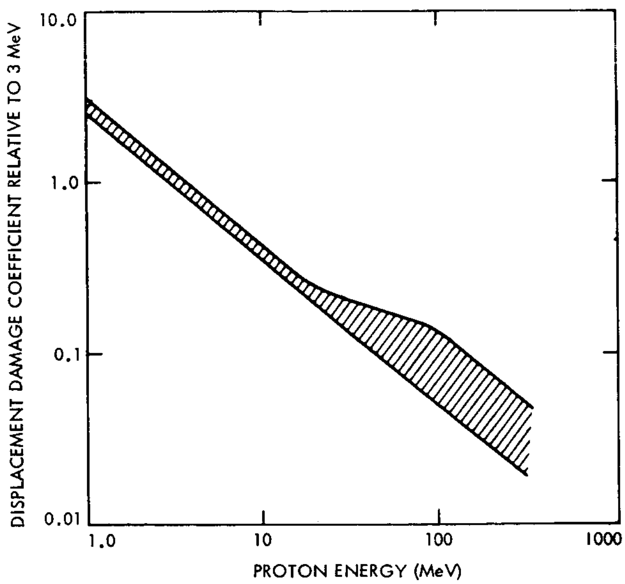

Figure 4. -Relative proton displacement damage in silicon.

must be selected large enough so that most of the protons will not be stopped by the spacecraft wall. The typical 50-mil aluminum wall will stop all protons with energy less than 15 MeV. Therefore, the worst-case characteristic energy is a compromise, the lowest value permitted by the model for which most of the protons in the spectrum will pass an assumed wall thickness.

ENERGY EQUIVALENCING

The same type of radiation effects data used to generate figures 1, 2, 3, and 4 may be used to construct relative damage functions dependent only on the particle type and energy. This procedure should be contrasted with attempts to develop equivalency in damage induced by different types of radiation, attempts which have led to inconclusive results. In energy equivalence, the requirement for testing in each predicted radiation environment remains. However, each type of exposure is reduced to a mono-energetic fluence; the relative damage function is used to collapse the energy-differential spectrum. Therefore, the test requirements avoid the serious problems of spectrum simulation. These same considerations also permit a comparison of the relative severity of environments consisting of different spectra of the same radiation type.

Although the absolute response, e.g., $\Delta(1/\beta)$, of a particular semiconductor device is strongly dependent on its electrical and physical characteristics, the relative response to a given fluence at one irradiation energy, normalized to the response at a reference irradiation energy, is reasonably device-independent. For example, in the case of transistors exposed to equal fluences of gamma radiation at different energies, for which the degradation of a particular electrical parameter is proportional to the dose, the relative damage function is proportional to the fluence-to-dose conversion factor. There is a lower limit in energy on the range of validity of the relative damage function, however, which is imposed by the effect of the device housing and geometry at low energy.

FLUENCE CALCULATIONS

Calculations of electron and proton fluences for Jupiter fly-by missions over a range of trajectories have been performed. The plane of the trajectory was taken to be the magnetic equatorial plane in each case. Upper limit and nominal fluences for some specific trajectories are listed in tables 1 and 2.

The determination of the fluences from the flux models consisted of an implicit time integration of the differential flux over the radial history of the trajectory. In the magnetic equatorial plane, the magnetic shell parameter L is equal to the radial distance from the center of the planet r, and the magnetic latitude is zero. Thus, the only time dependence in the flux is implicit in its radial dependence. Of course, it was necessary to select an arbitrary upper radial cut-off on the integration. One further assumption was made, the neglect of the radial dependence of the characteristic energy E_0, which greatly simplified the calculation by separating the radial and energy dependences. Finally, the relative damage function was used to eliminate the energy dependence, as described in the preceding section, and a mono-energetic fluence was obtained for each case.

Table 1. –Damage-weighted Jovian electron fluence (3 MeV).

MISSION NOTATION	TRAJECTORY PARAMETERS (JUPITER)		ELECTRON FLUENCE, e/cm^2	
	PERIAPSIS, R_J	DEFLECTION ANGLE, deg	NOMINAL	UPPER LIMIT
1976 JSP	1.1	136	7.4×10^{11}	7.5×10^{12}
1977 JSP	4.2	107.5	8.6×10^{10}	4.0×10^{12}
1977 JSP	5.6	85	3.7×10^{10}	2.9×10^{12}
1979 JUN	6.8	81	2.3×10^{10}	2.5×10^{12}
1979 JUN	10.3	60	6.8×10^{9}	1.5×10^{12}

Table 2. –Damage-weighted Jovian proton fluence (20 MeV).

MISSION NOTATION	TRAJECTORY PARAMETERS (JUPITER)		PROTON FLUENCE, p/cm^2	
	PERIAPSIS, R_J	DEFLECTION ANGLE, deg	NOMINAL	UPPER LIMIT
1976 JSP	1.1	136	8.2×10^{10}	5.4×10^{12}
1977 JSP	4.2	107.5	9.5×10^{9}	5.9×10^{12}
1977 JSP	5.6	85	4.1×10^{9}	5.4×10^{12}
1979 JUN	6.8	81	2.5×10^{9}	5.4×10^{12}
1979 JUN	10.3	60	7.5×10^{8}	4.9×10^{12}

Table 1 lists the calculated electron fluences for several trajectories, specified by the periapsis, in units of planetary radii, and the deflection angle between the incoming and outgoing asymptotes of the trajectory. The relative damage function for a 3-MeV reference energy was chosen to determine both nominal and upper limit 3-MeV equivalent fluences for these Jupiter-Saturn-Pluto (JSP) and Jupiter-Uranus-Neptune (JUN) missions. The results show that while the fluence decreases with increasing periapsis on the basis of both models, the upper limit fluences are quite insensitive to periapsis. It is also shown that the upper limit fluences are 1-2 orders of magnitude larger than the nominal values.

The calculated proton fluences for the same trajectories are given in table 2 in terms of 20-MeV protons. In the case of the severe proton model, the prediction of a flat radial distribution leads to fluences that are completely insensitive to periapsis. The larger uncertainties in the proton models result in a wider spread between the nominal and upper limit fluences, in the range of 2-4 orders of magnitude.

ASSESSMENT OF THE RADIATION HAZARD

At this point, the predicted proton and electron fluences should be compared with available information on the radiation sensitivity of semiconductor devices. Figure 5 indicates the fluences of 1-3 MeV electrons that will cause detectable degradation (unshaded bar) and serious degradation or total failure (shaded bar) for a few device types. The bar graph is based on a small set of data, but the large differences in radiation sensitivity of the specific devices within a category is reflected in the large uncertainties in each bar. Also noteworthy is the obvious susceptibility of MOS devices to electrons, in comparison to other device types. This contrast simply results from electrons efficiently causing ionization, to which MOS devices are most sensitive. Vertical lines are given to indicate the nominal and upper limit fluences for worst-case trajectories. It can be seen that, with the exception of discrete MOS devices, careful part selection will obviate the electron problem.

The corresponding information for 20-MeV protons in figure 6 shows that the protons are a more serious hazard. The bar graph, which is based on the results of a study (ref. 5), reflects the efficiency with which protons cause both ionization and displacement damage. Even the nominal value mission fluence would seriously damage many device types. The design of a spacecraft for survival in the upper limit proton environment requires both a complete screening of piece-parts for radiation tolerance and hardening by circuit design.

CONCLUSION

Although the near-Jupiter proton and electron environment poses a serious hazard to a fly-by spacecraft, the current best estimates of this environment have large uncertainties. If some improvements in the uncertainties were obtained, especially for protons, the stringency of the test levels and parts selection requirements could be relaxed. In particular, a reduction in the uncertainty of the radial dependence of the flux would introduce a sensitivity to the trajectory and would allow a trade-off in mission planning. Efforts to improve the models in this manner are currently planned.

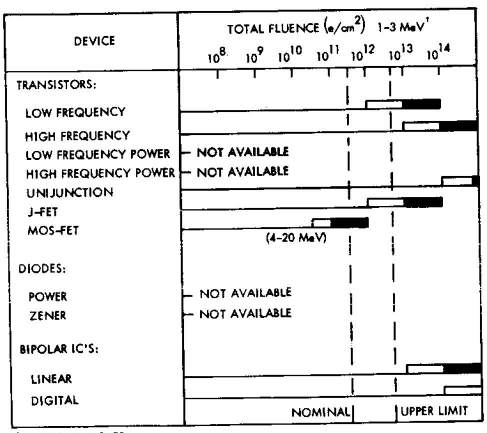

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Figure 5. - Typical tolerance of semiconductor devices to electron irradiation.

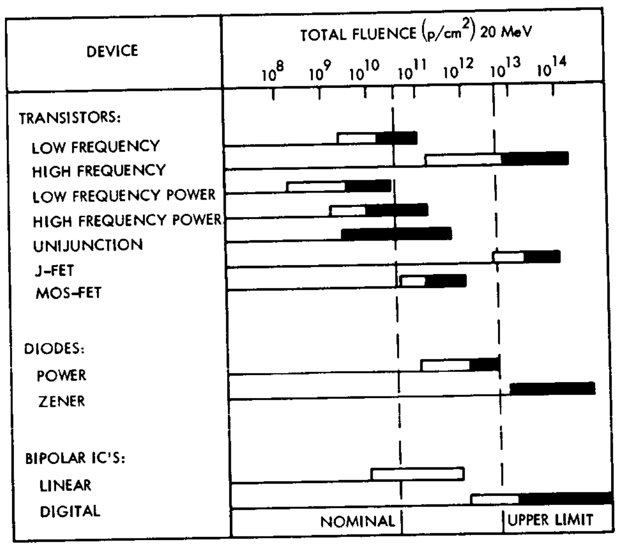

Figure 6. - Typical tolerance of semiconductor devices to proton irradiation.

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